Air-Sea Exchanges of Fresh Water: Global Oceanic Precipitation Analyses

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1. PROJECT SUMMARY

Oceanic Fresh water flux is an essential component of the global water cycle and plays an important role in forcing the oceanic circulation. However, its mean state, short-term variability and long-term changes are poorly monitored and documented due to undesirable qualities of the data sets for its two primary components, precipitation (P) and evaporation (E). Two major factors restricting the quality of existing oceanic fresh water flux data sets are 1) the lack of an extensive and continuous network of in-situ observations for calibrating and verifying each component, and 2) insufficient efforts to synthesize analyses for E and P. The availability of many new observation-based and model-produced data sets, especially precipitation, surface air temperature, sea surface temperature, humidity, and wind, makes it possible to quantitatively calibrate, verify and refine the existing P and E products.

In the past decade, two sets of satellite-based precipitation products have been developed at NOAA's Climate Prediction Center (CPC) that are used to monitor precipitation variations over global oceans. The CPC Merged Analysis of Precipitation (CMAP, Xie and Arkin 1997) is defined by merging individual products of satellite estimates derived from infrared (IR) and microwave (MW) observations. The CMAP data sets are created on a 2.5^{o}lat/lon grid over the globe and on monthly and pentad (5-day) time resolution for a 30-year period from January 1979 to the present. The other CPC oceanic precipitation analysis is that generated by the CPC Morphing Technique (CMORPH, Joyce et al. 2004) for high temporal / spatial applications. Cloud/precipitation movement vectors are first computed from high-resolution infrared image data in 30-min intervals observed by geostationary satellites. These movement vectors are then used to separately 'propagate' precipitation systems observed (by more-physically-based but less frequently sampled PMW observations) both forward/backward in time from "past"/"future" PMW scans to get the analyzed fields of precipitation at the targeted times. By weighting the forward and backward propagated rainfall estimates by the inverse of their respective temporal distance from scan time, these separate propagations are then morphed. The CMOPRH precipitation analysis is produced on an 8kmx8km grid over the globe from 60^{o}S to 60^{o}N and on 30-min intervals from December 2002. Both CMAP and CMORPH have been widely used by scientists around the world to a variety of applications including monitoring and assessment of global climate, model verifications and studies on global water budget/flux.

Further refinements of the CMAP and CMORPH are needed to improve their capacity to quantitatively document the precipitation variations and fresh water flux over the global oceans. The objectives of this project are to improve the CMAP and CMORPH precipitation analyses over ocean and to examine the fresh water flux as seen in the existing observations and in the NCEP Global Oceanic Data Assimilation System (GODAS). Specifically, we will

1) Provide the CMAP and CMORPH gridded analyses of oceanic precipitation, *together with estimates of uncertainty*, for a range of spatial and temporal scales consistent with data availability. Each product will be accompanied by a historical set of analyses of varying duration. The products will be updated and made available to the various communities of interest as promptly as the availability of input data permit, with lags ranging from less than one day to 3 months.

2) Monitor and assess the global oceanic fresh water flux using our precipitation analyses several of the available oceanic evaporation products and compare them with that generated by the NCEP operational Global Oceanic Data Assimilation System (GODAS). As part of this activity, we will examine the uncertainty of the fresh water flux derived from the current generation of observed precipitation and evaporation analyses to get insight into to what extent the differences between the flux in GODAS and observation are attributable to problems of the model.

3) Perform a set of modular research and development tasks to address critical shortcomings of the current precipitation analyses and to improve the existing products.

2. ACCOMPLISHMENTS

2.1. CMORPH Global Precipitation Analyses

The overall goal of this part of our project is to improve the CMORPH and to apply the technique to produce high-resolution oceanic precipitation for an extended period from 1998 to the present. Many recent studies (e.g. Ebert et al. 2007, Xie et al. 2007) have demonstrated that CMORPH provides high-resolution global precipitation satellite estimates with the best quantitative accuracy among similar products. The objectives of this part of our project are to further improve the CMORPH technique, to extend its record and to adjust the CMORPH for applications for quantitative monitoring of oceanic precipitation variability.

a) Development of next generation algorithm for the CMORPH

While the current version of the CMORPH algorithm is capable of producing global precipitation analysis in very high resolution (30min in time and 8kmx8km in space) and with high quality, it does not take full advantage of precipitation estimates from all available satellites, especially in the sense that information from IR derived rainfall estimates should be used for large temporal gap occasions between Microwave (MW) scans. Adopting the Kalman Filter technique enables us to utilize instantaneous precipitation estimates from all MW satellite observations available around the target time, and to a lesser degree IR derived rainfall, to optimally combine into a complete global field.

The basic idea of the Kalman Filter approach is to ‘propagate’ the instantaneous MW observations from their individual observation times to a target time using the cloud advection vectors derived from IR images and then to combine the propagated MW estimates with weights inversely proportional to the error variances. One important step in applying the Kalman Filter technique is to define error statistics (correlation) for the individual input MW precipitation estimates as a function of the time difference between the target global field and the MW observations. To this end, we compared propagated MW estimates against surface radar observations over the conterminous United States for each available satellite. As expected, the correlation decreases and the error increase with the propagation time (Figure 1). The correlation between the propagated satellite MW estimates and the ground truth (radar) is higher than 0.5 for concurrent observations but decreases to less than 0.2 when the MW estimates are propagated for 2.5 hours in each temporal direction or longer (or 5 hour combined period). MW estimates from different instruments present different error statistics. Overall, MW precipitation estimates from the TRMM TMI/AMSU exhibit the best/poorer performance in representing precipitation throughout the propagation time period examined. These statistics suggest that in addition to the MW observations, IR derived rainfall estimation is useful in filling temporal gaps larger than three hours between MW scans.

The satellite error functions are then utilized to define the global precipitation analysis from the propagated MW estimates through the Kalman Filter. Quantitative assessments are performed for the precipitation analysis generated by the Kalman Filter-based and the results showed significant improvements in the performance of the analysis in representing the spatial variations and temporal change of precipitation (red line Figure 2). Further work is underway to fine-tune the error statistics for various seasons and for different regions and to include information from additional new satellites to achieve the best possible performance. Temporally/spatially coincident MW rainfall estimation from the under-flying TRMM (and GPM for 2013 and beyond) relative to precipitation from each sun-synchronous MW equipped obiter will be used to determine the regional/seasonal skill/error characteristics needed to optimally combine the rainfall for the entire globe.

The results of this part of the work have been reported at couple scientific meetings and will be summarized into a journal paper once the entire process is completed.

b) Extending the CMORPH period of record back beyond December 2002

Currently, CMORPH high resolution precipitation estimates are available for a period from December 2002 to the present. As an important part of this project, we are in process of extending the CMORPH data record back for the period to November 1998. This will generate a 10-year complete record of high-resolution precipitation over the global land and ocean.

The backward extension of the CMORPH has been delayed due to the transition of the computer systems at the NOAA Climate Prediction Center (CPC). However, we were able to finish the collection of all the satellite data necessary for the backward extension, develop, test, and benchmark the retrospective analysis system on the new computer system, and start the backward extension. As of the end of the FY2008, we have finished the backward extension from December 2002 to September 2002 and the extension is undergoing at a pace of 4 months of data reprocessing in a month. We expect the backward extension of the CMORPH analysis for the entire data period will be complete in the next fiscal year. The CMORPH satellite precipitation estimates for the extended period are being made available through the CPC ftp server upon the completion of final check. Shown in Figure 3 is an example of the CMORPH precipitation for 00Z, October 13, 2002. CMORPH is capable of depicting large-scale distribution as well as fine structures of global oceanic precipitation with high quantitative quality.

Preliminary results of this CMORPH backward extension has been reported at the Annual AGU assembly.

c) Adjusting the CMORPH against a long-term data record

Construction of the CMORPH global high-resolution precipitation analysis enables a variety of applications in monitoring, documenting and diagnosing oceanic precipitation. Its data record (from 1998), however, is insufficient for the creation of a robust climatology, making it difficult to define anomaly. To overcome this limitation, we have taken a straightforward and effective approach to adjust the high-resolution CMORPH precipitation analysis for recent years to a long-term record with a coarser resolution so that anomaly patterns can be defined for the adjusted CMORPH against the climatology of the long-term record.

The GPCP pentad precipitation analysis of Xie et al. (2003) is used as the reference long-term precipitation data against which the high resolution CMORPH precipitation estimates are adjusted. The GPCP pentad (5-day) precipitation analysis is constructed on a 2.5^{o}lat/lon grid over the global by merging information from multiple satellite observations and in situ measurements. The analysis starts from January 1979 and is updated on a real-time basis at NOAA Climate Prediction Center.

Ratio between the original CMORPH and the GPCP pentad analysis is computed for each 0.25^{o}lat/lon grid box and for each day by comparing the accumulated precipitation amount over a 2.5^{o}lat/lon GPCP grid box covering the target grid and over a 15-day period ending at the target date. The ratio is then multiplied to the original CMORPH. The adjusted CMORPH presents overall quantitative consistency with the GPCP pentad analysis (Figure 4) while retains the high-resolution information in the original CMORPH (Figure 5). To facilitate the definition of anomaly for the adjusted CMORPH, GPCP pentad precipitation climatology for 1979 – 1995 (CPC official base period for satellite observations) is desegregated into daily and 0.25^{o}lat/lon resolution using the adjusted CMORPH mean precipitation fields for recent years, enabling quantitatively assess and monitor the oceanic precipitation on a very high resolution. Further work is underway to apply this method for real-time applications. Once completed, the adjusted CMORPH high-resolution oceanic precipitation analysis will be provided to CPC ocean group for monthly global ocean monitoring.

2.2. CMAP Global Precipitation Analyses

This part of our research project involves two components: 1) documentation of the global oceanic fresh water flux using the CMAP and other observation-based data sets of precipitation and evaporation; and 2) Continuous updates and improvements of the current CMAP for better quantitative applications over ocean.

a) Documentation of the global oceanic fresh water flux

Majority of the work on this topic has been done during FY2007, including the examination of the mean climatology and seasonal variations of fresh water flux as depicted by observations and how they are reproduced by several NCEP model-based products. In FY2008, we continued our efforts to examine the interannual variation patterns of oceanic precipitation and evaporation patterns associated with large-scale patterns including ENSO, PNA, and MJO. As shown in Figures 6 and 7, in general the magnitude of the evaporation anomaly associated with ENSO is much smaller (~1/5) than that of precipitation. All of the NCEP model-based products (CDAS1, CDAS2, CFS, and GDAS) are capable of reproducing the ENSO-induced large-scale patterns, especially for precipitation. The evaporation anomaly pattern generated by the NCEP Climate Forecast System (CFS), however, presents relatively poor agreements with that of the observations. These results have been reported at the 3rd International Conference on Reanalysis and a paper describing our work on the examination of oceanic fresh water flux in the NCEP model-based products has been almost completed, pending submission to the special issue of the reanalysis conference (to be announced by the organizers).

b) Updates and improvements of the oceanic precipitation data sets

The CMAP precipitation analysis has been updated routinely and made available to the science community and general public through the CPC ftp server (ftp.cpc.ncep.noaa.gov/precip). As of October, 2008, the CMAP data set is available for a 30-year period from January 1979 to August 2008.

One major shortcoming of the current generation global oceanic precipitation analyses, including those of GPCP, CMAP, and TRMM, is its uncertain magnitude which is crucial in many applications such as the examination of oceanic fresh water flux and energy budget. While efforts have been made by many satellite algorithm developers to improve the quantitative accuracy of satellite retrievals over ocean, it is necessary to include the information of direct measurements of precipitation from in situ platforms. During FY2008, we performed comprehensive examinations of the biases in the satellite precipitation estimates and developed a prototype algorithm to remove the satellite bias through matching the probability density function (PDF) of the satellite estimates against that of the co-located in situ measurements. Matching pairs of the gauge and satellite data are collected over grid boxes with at least one gauge over a spatial domain of 10^{o}lat/lon centering at the target grid box and over a time period of 30-days ending at the target date. Cumulative PDF functions are then defined for the satellite and gauge data, respectively. Bias in the satellite estimates is finally identified and removed by matching the cumulative PDF of the satellite estimates with that of the gauge analysis.

Satellite observation and in situ measurements of precipitation over China are used for our experiments. The relatively dense gauge network there provided us with test cases to examine the sensitivity of the bias correction results to the gauge network density. Cross-validation is performed for the PDF matching technique and results showed successful correction of the bias over regions with reasonable in situ gauge networks (Table 1).

The results of this work have been presented at several scientific meetings. Further work is underway to examine the impact of the gauge network with inadequate distribution density and configuration to the effectiveness of the bias correction.

3. PUBLICATIONS

3.1. Journal Papers

Joyce, R. J., Pingping Xie, Yelena Yarosh, John E. Janowiak and Phillip A. Arkin, 2008: The use of TRMM data in the CMORPH suite of precipitation analyses, Special Issue on Precipitation Measurements from Space, *J. Meteor. Soc. of Jpn.*

Joyce, R. J. Pingping Xie, Yelena Yarosh, John E. Janowiak and Phillip A. Arkin, 2009: CMORPH: A 'Morphing' Approach for High Resolution Precipitation Product Generation, Book Chapter for Springer Book Volume on 'Satellite Applications for Surface Hydrology' planned for publication in 2009.

Xie, P., W. Wang, J.E. Janowiak, M. Chen, C.L. Shie, and L. Chiu, 2009: Examining fresh water flux over global oceans in the NCEP CDAS, CDAS2, GDAS, GFS and CFS. To be submitted to the special issue for the 3rd *WCRP International Conference on Reanalysi*s.

3.2. Conference Presentations

Joyce, R. and P. Xi e, 2007: Kalman filter approach to CMORPH: a skill and error assessment of instantaneous and propagated passive microwave estimated rainfall, *Pilot Evaluation of High Resolution Precipitation Produc*ts (PEHRPP) workshop, 3-5 December, 2007, Geneva.

Joyce, R., and P. Xie, 2008: A Kalman Filter Approach to CMORPH Passive Microwave Rainfall Estimation, *IGARSS meeting*, Boston, MA, 6-11 July 2008.

Joyce, R. and P. Xie, 2008: A Kalman filter approach to blend various satellite estimates in CMORPH. *4th International Precipitation Working Group Meeting*, Oct. 13 0 17, 2008, Beijing, China.

Xie, P., W. Wang, J.E. Janowiak, M. Chen, C.L. Shie, and L. Chiu, 2008: Examining fresh water flux over global oceans in the NCEP CDAS, CDAS2, GDAS, GFS and CFS.

Third WCRP International Conference on Reanalysis. Tokyo, Japan, Jan. 28 – Feb.1, 2008.

Xiong. A.Y., P. Xie, J.-Y. Liang, Y. Shen, J.E.. Janowiak, M. Chen, and P.A. Arkin, 2008: Merging gauge observations and satellite estimates of daily precipitation over China. *4th International Precipitation Working Group Meeting*, Oct. 13 0 17, 2008, Beijing, China.

Yarosh, Y., P. Xie, and R. Joyce, 2008: Retrospective CMORPH Reprocessing Efforts, *Spring AGU Joint Sessions*, 26 – 30 May, 2008 Fort Lauderdale, FL.

4. REFERENCES

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Ebert, E. E., J. E. Janowiak, and C. Kidd, 2007: Comparison of Near Real Time Precipitation Estimates from Satellite Observations and Numerical Models. *Bull. Amer. Meteor. Soc.*, DOI:10.1175/BAMS-88-1-47

Joyce, R.J., J.E. Janowiak, P.A. Arkin, and P. Xie, 2004: CMORPH: A method that produces global precipitation estimates from passive microwave and infrared data at high spatial and temporal resolution. *J. Hydrometeor.*, **5**, 487 – 503.
climatology. *J. Climate*, **12**, 2850 – 2880.

Xie, P., and P.A. Arkin, 1997: Global precipitation: A 17-year monthly analysis based on gauge observations, satellite estimates, and numerical model outputs. *Bull. Amer. Meteor. Soc.*, **78**, 2539 – 2558.

Xie, P., J.E. Janowiak, P.A. Arkin, R. Adler, A. Gruber, R. Ferraro, G.J. Huffman, and S. Curtis, 2003: GPCP pentad precipitation analyses: An experimental data set based on gauge observations and satellite estimates. *J. Clim.*, **16**, 2,197 – 2,214.

Xie, P., M. Chen, A. Yatagai, T. Hayasaka, Y. Fukushima, and S. Yang, 2007: A gauge-based analysis of daily precipitation over East Asia. *J. Hydrometeor.*, **8**, 607 – 626.

5. FIGURES

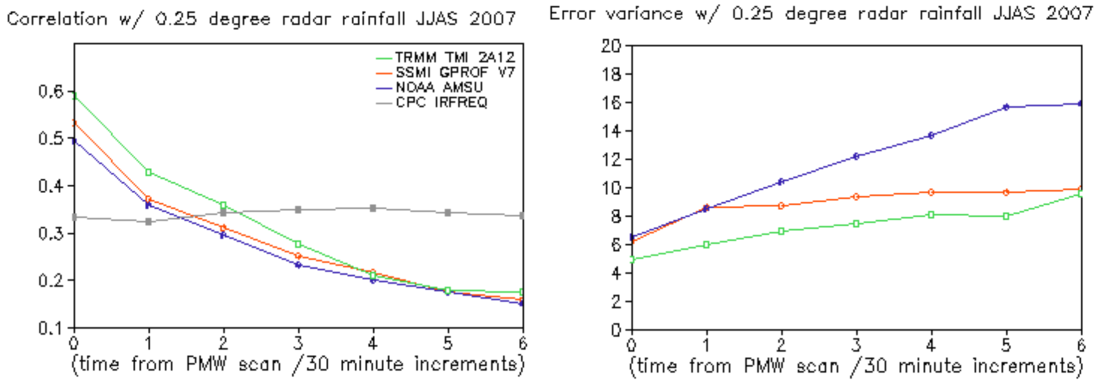

Figure 1. Correlation (left) and error variance (right) of forward propagated PMW rainfall relative to hourly 0.25 degree Stage II radar for JJAS 2007, x-axis = temporal distance to PMW scan time.

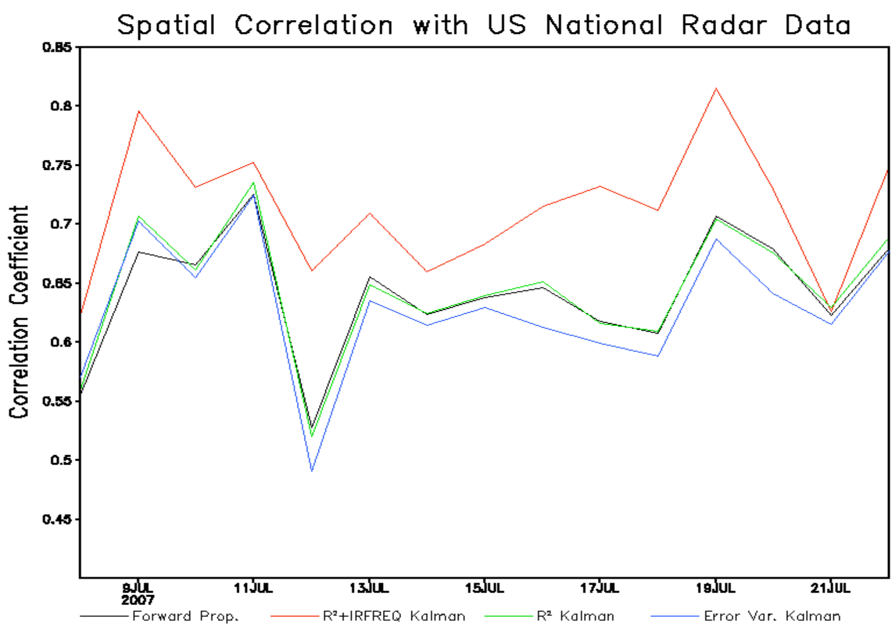

Figure 2. Validation results (correlation) for the operational and experiment versions of CMORPH over CONUS.

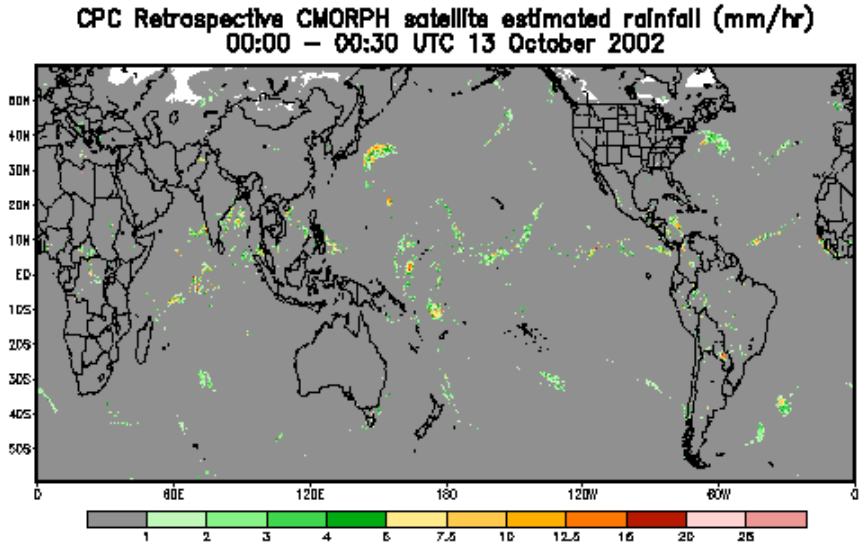

Figure 3. Sample CMORPH 30-min precipitation distribution for 00:00-00:30Z, 13 October, 2002.

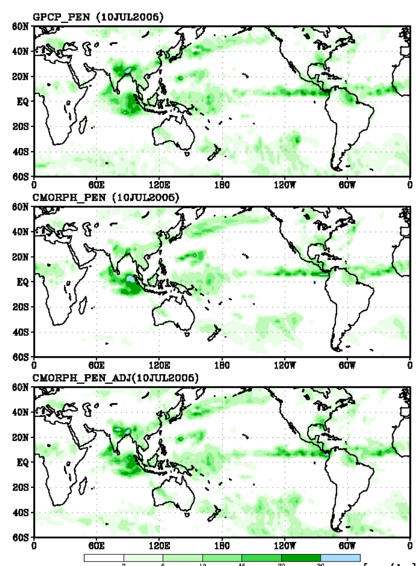

Figure 4. Spatial distribution of pentad precipitation of GPCP (top), original CMORPH (middle), and adjusted CMORPH for the 39th pentad (July 10-14) of 2005 (mm/day).

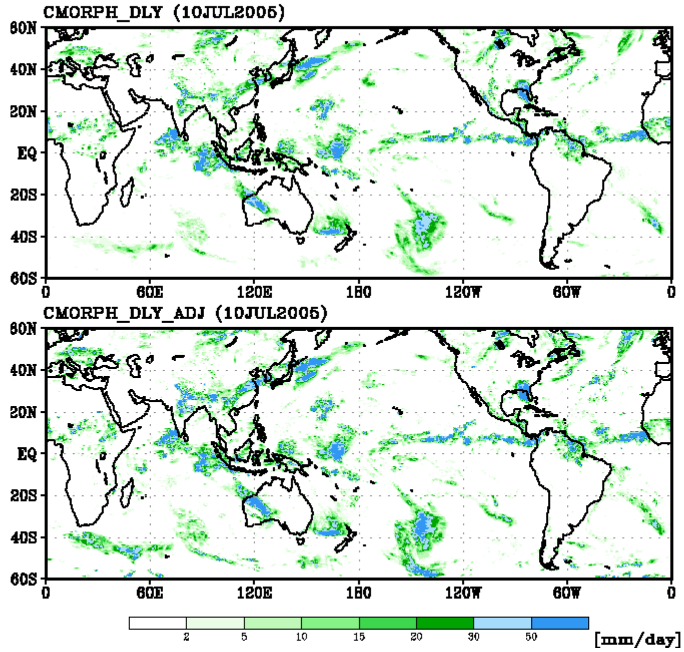

Figure 5. Spatial distribution of daily precipitation of original CMORPH (upper) and adjusted CMORPH for July 10, 2005 (mm/day).

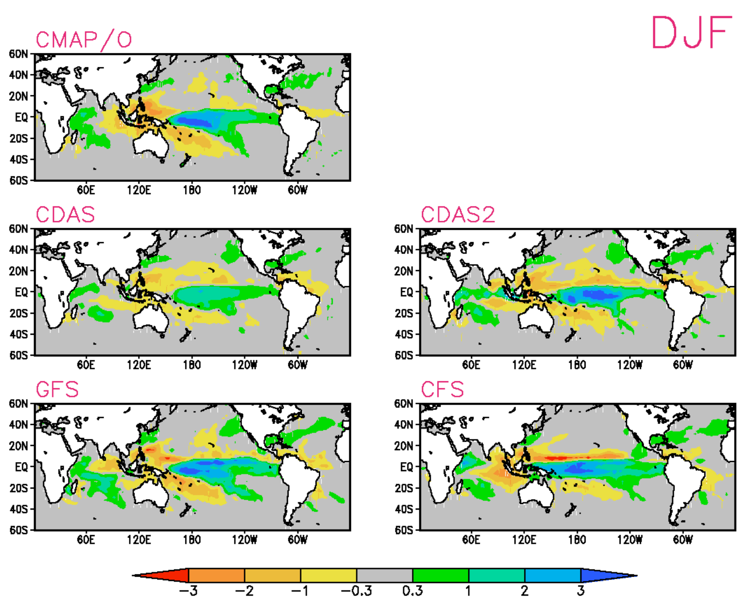

Figure 6. Regressional coefficients of December-January-February (DJF) precipitation anomaly (mm/day) against the NINO3.4 index for precipitation generated by the observation (CMAP), NCEP Reanalysis 1 (CDAS), NCEP Reanalysis 2 (CDAS2), NCEP Global Forecast System (GFS) AMIP simulations, and NCEP Climate Forecast System (CFS) CMIP simulations.

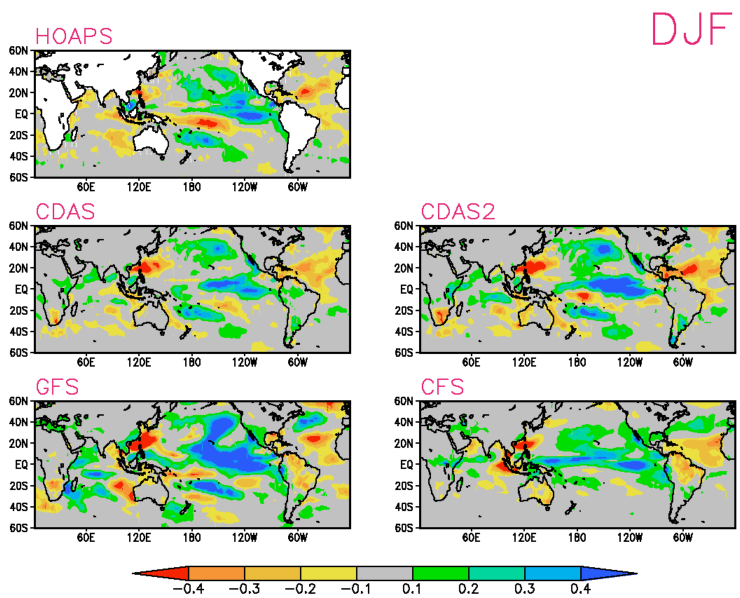

Figure 7. Regressional coefficients of December-January-February (DJF) evaporation anomaly (mm/day) against the NINO3.4 index for precipitation generated by the observation (HOAPS), NCEP Reanalysis 1 (CDAS), NCEP Reanalysis 2 (CDAS2), NCEP Global Forecast System (GFS) AMIP simulations, and NCEP Climate Forecast System (CFS) CMIP simulations.

Table 1. Cross-Validation Statistics for the original and bias-corrected CMORPH.

CMORPH	Bias (%)	Correlation
Original	**-9.7%**	**0.706**
Bias-Corrected	**-0.0%**	**0.785**